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# Study on Effect of Subsurface Dam in Coastal Seawater Intrusion

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## ABSTRACT

For increasing storage of fresh groundwater and prevention of seawater encroachment, a quasi three-dimensional, two phases flow groundwater model to simulate the movement of interface between seawater and freshwater has been applied in the study area. With this model, regional groundwater flows and interface movements in coastal aquifer are numerically solved. A subsurface dam is planned and evaluated to protect the fresh groundwater resource. With the numerical analysis, a serious encroachment will not occur if the subsurface dam is constructed. Several evaluations are made for the feasible exploitation based on the hydrological budge.

## INTRODUCTION

The seawater intrusion in coastal aquifer has long been widely attracting an attention of researchers for the management of coastal water resource and environment protection. It is worthwhile note that human water-use patterns are the most important factors for seawater intrusion. Seawater intrusion is practically density dependent problem. Owing to the density difference, the seawater intrusion into freshwater aquifer would usually happen in both vertical and lateral direction if groundwater were excessively pumped in the sensitive portions of the freshwater aquifer. This problem, therefore, has become an important factor that affects decisions related to exploitation strategies of freshwater resources.

In general, two kinds of general approaches have been usually used to analyze seawater intrusion in coastal aquifer: the dispersed interface and the sharp interface. In the dispersed interface research, one of the principal complexities in modeling is how to simulate accurately the movement of the transition zone between fresh/saltwater generated by hydrodynamic dispersion. Numerous researchers have made quantitative analyses system in an attempt to describe mathematically the physical system and its important mechanisms (Coope, et al., 1964, Bear and Dagan, 1964, Pinder and Page, 1977). Sa da Costa and Wilson [1979] extended the model of Shamir and Dagan [1971] to describe the propagation of the sharp interface in a two-layer coastal aquifer. Using a finite element method, they obtained that the rate of the toe propagation decreasing hydraulic conductivity of the bottom porous layer. Shapiro et al. [1983] and Essaid [1990] developed similar models for two-dimensional two-layer aquifer system to simulate coupled freshwater and seawater flow separated by sharp interface. They numerically calculated the evolution of the toe and tip locations of the interface in each layer.

In this study, For the solutions of above problem, synthetic researches have been conducted. Herein, a numerical model is employed to examine the coupled freshwater and seawater flow separated by a sharp interface, to assess the position of the interface between them and the alternative schemes of groundwater development for the island phreatic aquifer. The effect of the subsurface dam is evaluated as an alternative strategy for future developing and managing of the freshwater resources. The evaluation schemes are presented to determine the quantity that can be developed without inducing groundwater quality degradation due to seawater intrusion. It is hoped that the evaluation of the subsurface dam will assist in future groundwater resource planning.

## PRINCIPLE EQUATION

With the approximations of Ghyben-Herzberg conceptual model, under the condition of several reasonable simplification and assumptions to simplify the physical processes of freshwater and seawater flow being satisfied, the two-fluid, sharp interface model is a quasi-three dimensional partial difference model. It simultaneously solves the freshwater and seawater fluid equations by the condition that the pressure is equal on either side of the interface. It is assumed that the flow within the aquifer is predominantly horizontal, therefore, the vertical flow can be neglected within the aquifer, and permeability is constant along the vertical direction.

The following continuity equation (1) and (2) can describe the seawater and fresh water flow, respectively.

$$n_e \frac{\partial h_s}{\partial t} = -\frac{\partial (h_s \cdot u_s)}{\partial x} - \frac{\partial (h_s \cdot v_s)}{\partial y} \tag{1}$$

$$n_e \frac{\partial (h_f - h_s)}{\partial t} = -\frac{\partial \{(h_f - h_s) u_f\}}{\partial x} - \frac{\partial \{(h_f - h_s) v_f\}}{\partial y} + f\hat{A} \tag{2}$$

The basic velocity equations for flow through porous media are given by the Darcy's equation as:

$$u_s = -k_s \frac{\partial \varphi_s}{\partial x}, \quad v_s = -k_s \frac{\partial \varphi_s}{\partial y} \tag{3}$$

$$u_f = -k_f \frac{\partial \varphi_f}{\partial x}, \quad v_f = -k_f \frac{\partial \varphi_f}{\partial y} \tag{4}$$

where $u_s$ and $u_f$ are Darcy's velocities and $k_f$ and $k_s$ are Darcy's permeability for freshwater and seawater phase, respectively.

At a point position ($z$) of the seawater phase, $\varphi_s$ is given as following relation

$$\begin{aligned} \varphi_s &= z + \frac{(h_s - z)\cdot \rho_s \cdot g + (h_f - h_s)\cdot \rho_f \cdot g}{\rho_s g} \\ &= \left(\frac{\rho_f}{\rho_s}\right)\cdot h_f + \left(\frac{\Delta\rho}{\rho_s}\right)\cdot h_s \end{aligned} \tag{5}$$

where $\Delta\rho$ is the density difference equals to $\rho_s - \rho_f$.

And in a point position ($z$) of the freshwater phase, $\varphi_f$ is given as

$$\varphi_f = z + \frac{(h_f - z)\cdot \rho_f \cdot g}{\rho_f \cdot g} = h_f \tag{6}$$

The final forms of the partial differential equations are obtained as follows

$$\frac{n_e}{k}\frac{\partial h_s}{\partial t}=\frac{\rho_f}{\rho_s}\left\{\frac{\partial h_s}{\partial x}\frac{\partial h_f}{\partial x}+h_s\frac{\partial^2 h_f}{\partial x^2}\right\}+\frac{\Delta\rho}{\rho_s}\left\{\left(\frac{\partial h_s}{\partial x}\right)^2+h_s\frac{\partial^2 h_s}{\partial x^2}\right\}$$
$$+\frac{\rho_f}{\rho_s}\left\{\frac{\partial h_s}{\partial y}\frac{\partial h_f}{\partial y}+h_s\frac{\partial^2 h_f}{\partial y^2}\right\}+\frac{\Delta\rho}{\rho_s}\left\{\left(\frac{\partial h_s}{\partial y}\right)^2+h_s\frac{\partial^2 h_s}{\partial y^2}\right\} \qquad (7)$$

$$\frac{n_e}{k}\frac{\partial h_f}{\partial t}=\frac{n_e}{k}\frac{\partial h_s}{\partial t}+\frac{\partial h_f}{\partial x}\left\{\frac{\partial h_f}{\partial x}-\frac{\partial h_s}{\partial x}\right\}+\left(h_f-h_s\right)\frac{\partial^2 h_f}{\partial x^2}$$
$$+\frac{\partial h_f}{\partial y}\left\{\frac{\partial h_f}{\partial y}-\frac{\partial h_s}{\partial y}\right\}+\left(h_f-h_s\right)\frac{\partial^2 h_f}{\partial y^2}+\varepsilon \qquad (8)$$

where $n_e$ is effective porosity in the phreatic aquifer; $k$ is hydraulic permeability of the aquifer (neglecting the variation of $k_f$ and $k_s$ in the aquifer); $h_f$ is the height of the freshwater above the reference point; $h_s$ is the height of the seawater above the reference point; $\varepsilon$ is the volumetric flow rate of sources or sinks per unit area, x and $y$ are coordinates direction.

Herein, the explicit finite difference scheme was selected for solving the above problem (Ueta and Fujino *et al*, 1981).

## AQUIFER SYSTEM IN THE RESEARCH AREA

The study area is located at an Island in the northern Okinawa prefecture of Japan, which covers approximately 15.4 km$^2$ (Fig.1). There are not sufficient surface water resources for utilization because of the island’s geographic condition in spite of very high annual precipitation (average 1,856 mm/year). It has been necessary to rely on groundwater resources for the extensive irrigation and drinking water demand. It will become increasingly important to further aquifer development in the area.

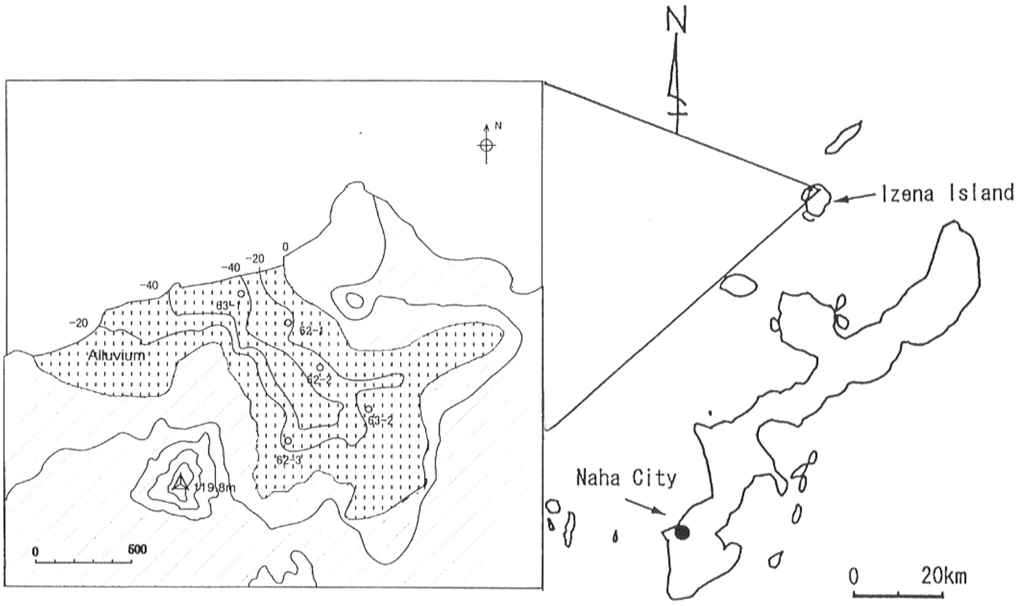


Figure 1 Location of study area

The island area includes portions of the northern coastal slope lowland and the southern mountains. The maximum elevation difference is about 115 m and most of the lowland is farmland. The Mt.Ohno is the highest mountain in the island with an elevation of 119.9 m. the watershed is bounded to the south by Mt.Tenjyou (102.3m) and east trending hills whose elevations range from about 30 to 120 m around the lower central lowland. The lowland becomes gradually extender toward southern except a narrow part in the 300 m from the coastline.

The geological framework that forms the objective aquifer consists of the upper alluvial formation units which are an unconsolidated alternating layers of fine sand and middle sand containing the fragment of coral, and shell etc. The deposited thickness is more than 25 meters in the central part and average 15 meters in the edge.

Underlying the upper aquifer, there is a continuous clay layer, which is approximately 2-3 m thickness at the center of the basin and generally thins toward the south and the margins of the lowland. This clay layer separates the shallow groundwater aquifer from a deeper sedimentary and can act as an impermeable basement layer of the aquifer system. The hydraulic permeability for the above principal hydrological units tends to gradually decrease downward. Several investigations and pumping tests have been undertaken to determine the hydraulic characteristic of the aquifer. By the field measurement, the saturated hydraulic permeability of upper alluvial unit is $5.82\text{-}6.50\times10^{-4}$(m/s) and gradually decreases to $1.01\times10^{-6}$ (m/s) in lower unit. These parameters will be adopted as assumption of the permeability in the following numerical model. In the area, groundwater supplies a relatively large proportion of available water. The groundwater tables are automatically recorded by using automatic water-level recorders in five monitoring wells.

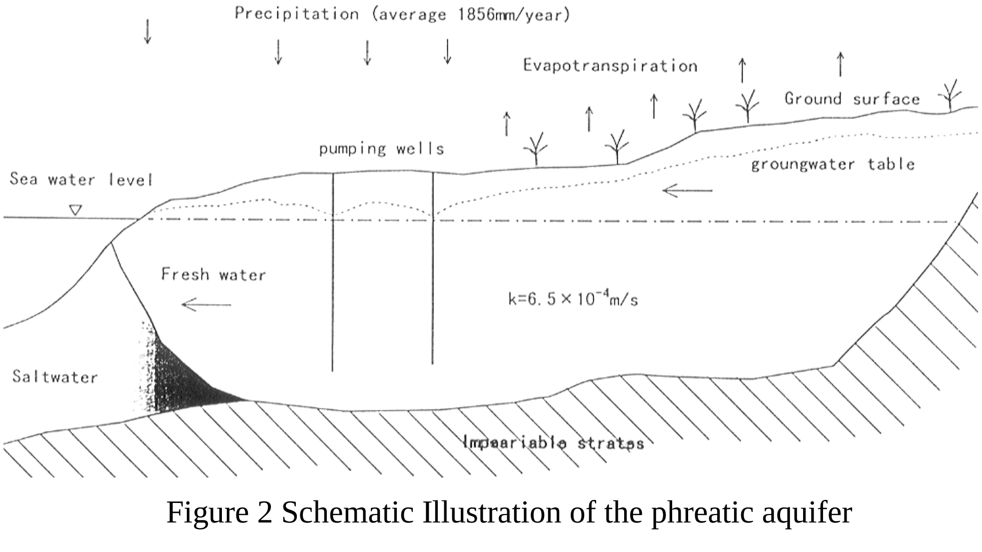


Figure 2 Schematic Illustration of the phreatic aquifer

The precipitation is considered as the major groundwater recharge, which controls the fluctuation of the groundwater. The recharge model was derived from a tank method to estimate infiltrate recharge under variable precipitation and soil condition. An analysis of groundwater recharge from precipitation shows that about $1.6\times10^{6}$ $m^3$/y (cubic meter per year) of precipitation falls on the ground surface in the 1991, of which about $4.1\times10^{5}$ $m^3$/y is estimated to recharge the aquifer system. It means that the annual net recharge is about 25 percent of the annual precipitation. The aquifer recharge is the replacement of groundwater that may be pumped out or lost by natural processes. Evaluation of the recharge rate of the aquifer is a critical step for determining the amount of available groundwater in long-term withdrawal, which leads to a safe and reliable groundwater supply. Based on the preliminary results presented in this research, a considerable volume of groundwater is discharged by evapotranspiration from the aquifer system. By the observation and modeling, more than 1,090 mm per year of evapotranspiration is furnished by the aquifer system (Y.Ru and K.Jinno *et al*, 1996). This means that the infiltration and the evapotranspiration are important factors in groundwater research.

## HYDROGEOLOGICAL CONCEPT MODEL

Figure 3 shows the simulated extent and the plane boundary of the aquifer system for a regional analysis. The directions of the x and y-axis are taken as positive in the horizontal plane. The boundary a-b represents the coastline, and it is the source of the seawater intrusion into the aquifer. Other inland boundaries are simplified as impervious boundaries of the whole system in x-y plane.

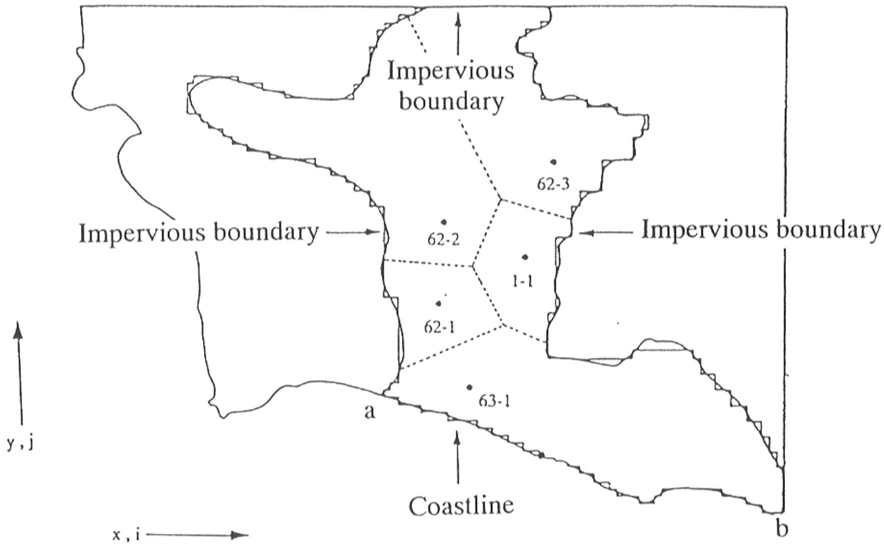


Figure 3 Hydrogeological concept model

Using the finite difference method, the numerical solutions of the differential equation are solved. The calculation area is discretized into square mesh along the $x$ and $y$ directions. Finite difference grid consisted of 67 rows by 80 columns, with the grid block of each element have dimensions of $\Delta x \times \Delta y$ = 25 by 25 m over the domain and the total number of elements is 2,177. Space and time are discretized in solving the functions $h_f$(x,y,t) and $h_s$ (x,y,t). Before assessing the movement and location of the interface between seawater and freshwater, the present conditions were simulated to identify some of the parameters in the numerical model and to determine the initial condition for the simulation. The model parameter values of the aquifer were initially chosen on the basis of available data obtained from the field test. The simulation period of the groundwater flow was chosen from March 1991 to February 1992. Because the total precipitation of this period is closed to drought hydrologic year in the study area, in which there is the less influence from outside interrupting than other years.

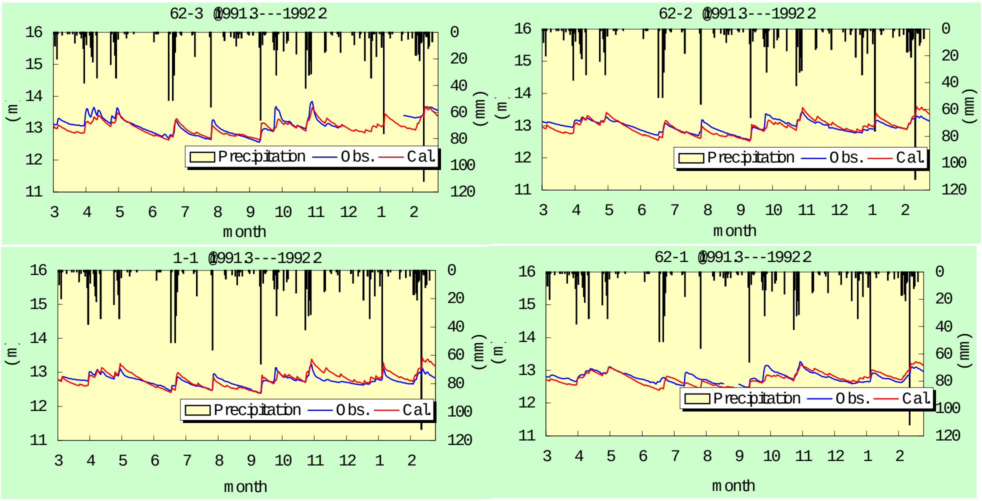


Figure 4 Comparison of simulated result and field observed groundwater table

Figure 4 shows the comparison of simulated result and field observed groundwater table during the whole calculation period at selected four observation wells. It is found that the numerical solution could give acceptable result for the position of the interface in a vertical cross section and in plane distribution. Under the condition of precipitation in 1991, the interface front was found at about 225 meters from the coastline in the central part of the aquifer. This was adopted as the initial condition for further prediction on the movement of the interface. With the different precipitation recharge rate, the movement of the interface responding to the rate is slow.

To assess the future-developing situation, the two pumping schemes of groundwater pumping well and collecting water ditch (Fig.5) were employed considering the 1991 water cycle as the basis for simulation groundwater flow.

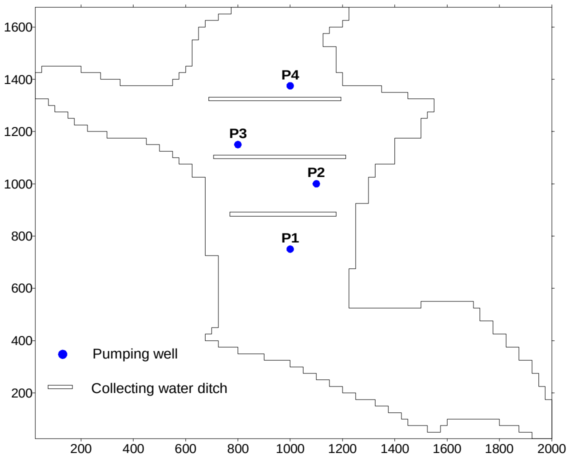


Figure 5. Locations of the pumping well and ditch

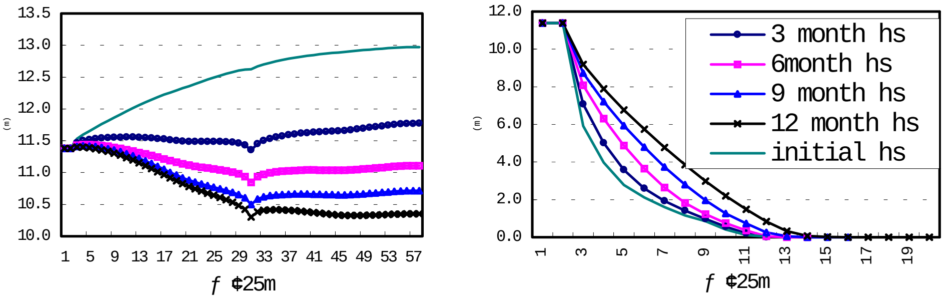


Figure 6. The groundwater tables and position of the interface

The sensitivity of the numerical model was verified with the follow condition: Design four planed pumping wells to withdrawal groundwater according to the aquifer characteristics; The range of pumping rates is from 50 to 250m$^3$/d at each of the planed wells, respectively; Continuously withdrawal over the designed four periods: 3, 6, 9 and 12 months; Evapotranspiration in 1991 is used as the natural discharge of the aquifer. The precipitation is assumed as zero and 1991 rainfall.

The groundwater tables and position of the toe of interface were simulated under the condition of gradually increasing the pumping rate from 50 to 250m$^3$/day. Figure 6 shows the groundwater table variation and the interface movement after 3, 6, 9, and 12 month in vertical cross section. With the time increasing, it is obvious both the depression of the groundwater tables and the intrusion of the seawater. Figure 7 show the groundwater tables and position of the toe of interface under the condition of gradually increasing the pumping rate. It can be seen that after 365 days of the constant pumping rate, the toe of the interface would reach to inland more than 575 m continually**.**

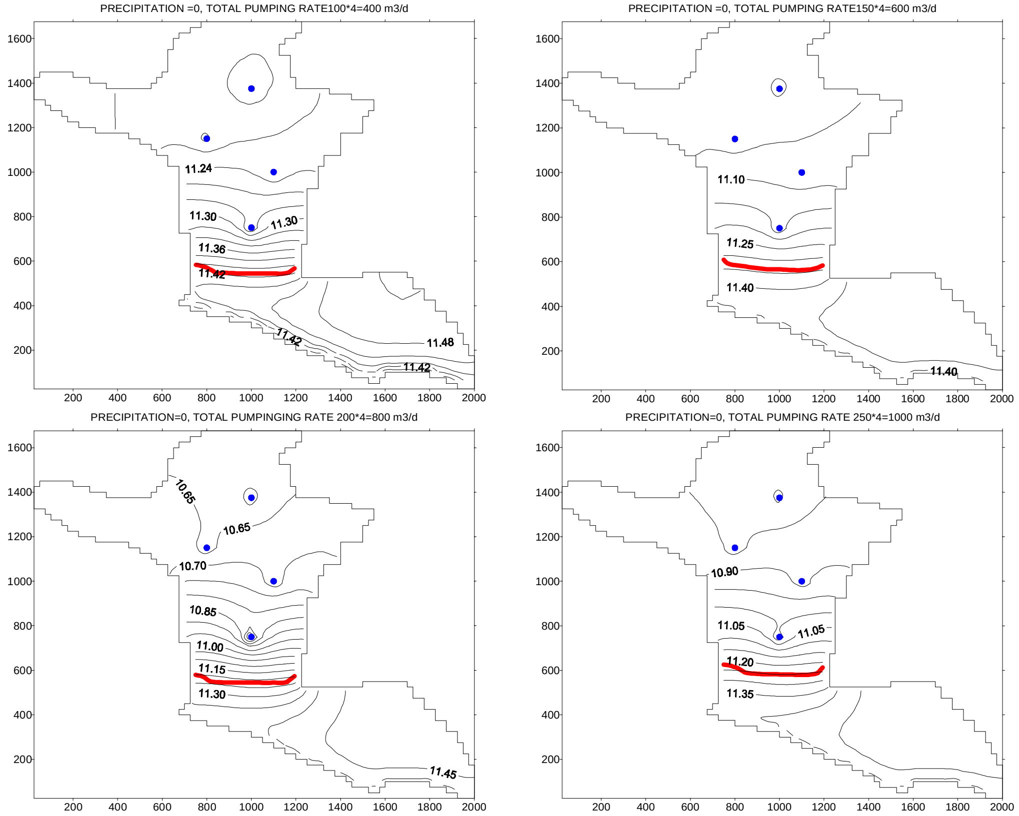


Figure 7 The groundwater tables and variation of the interface

The groundwater withdrawal would product a major effect on the movement of the interface. Firstly, the quantity of groundwater flow out to the sea would be reduced, the movement of the interface would advance slightly inland the aquifer would be contaminated gradually. The equilibrium state of fresh/seawater would be broken, and it is unavoidable to cause the interface front moving forward to the landsite continuously. In the study area, the maximum pumping capacity of each well is about 250m$^3$/d (Note that this quantity is an extremely withdrawal condition, and in practical condition, the quantity of the groundwater withdrawal can be not pumped at the constant rate simultaneously). The more intrusion was brought about for the largest pumping rate and the long period pumping. Enlarging groundwater withdrawals from this aquifer would change the patterns of groundwater flow that discharge to coastal ecosystems before. The mutual interference among the pumping wells would be a practical issue in future groundwater development because of the limited extent in the island aquifer system. It is very difficult to maintain water supply for long-term pumping with the pumping rate of 200-250 m$^3$/d in each well.

## EFFECT OF THE SUBSURFACE DAM

The previous analyses of the numerical simulation point out that increasing pumping groundwater has large influence on the interface and the large cones of depression would appear. On the other hand, under natural condition, most infiltration recharges of the precipitation are flowed out through aquifer into the sea. Obviously, it should be considered simultaneously that how to utilize effectively the groundwater outflow for increasing development groundwater in coastal aquifer and the problem of preventing seawater intrusion. To the study aquifer, lateral seawater movement was considered as a major threat to the freshwater resources. Herein, synthetic considering the characteristics of the groundwater resource, geological and topographical conditions, the method of constructing impervious subsurface dam is suitable and necessary for solving the contradiction of the water supply if the more groundwater is withdrawn to meet the demand of the island agricultural development.

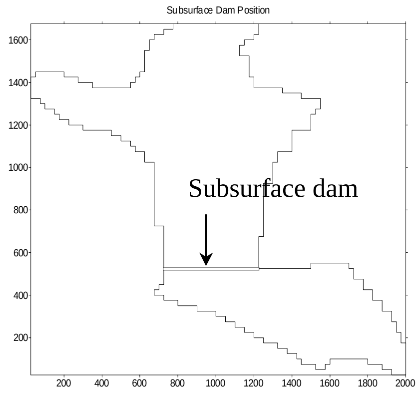


Figure 8 The plan position of the subsurface dam

The topographical and geological conditions in the study area provide the technical possibility of constructing the subsurface dam. The site of groundwater dam is designed at most narrow valley; where is about 500 m in length (Fig.8) and can also reduce construction costs and make it favorable for controlling seawater intrusion. This effective measurement has been successively employed at some other places in the world.

### *Subsurface dam permeability*

In the simulation of the effect of the subsurface dam, the permeability ($k_{dam}$) in the site of subsurface dam was assumed as the follow relation:

$$k_{dam} = \frac{\Delta w_d \cdot k_a}{\Delta m} \tag{12}$$

where $\Delta w_d$ is the width of the subsurface, $\Delta m$ is the length of a finite difference grid in the calibration model, and $k_a$ is the aquifer permeability.

*The pumping well scheme*

In this scheme, the pumping condition is agreement with the simulated pumping rate in order to examine the consequence of increased pumping rate at the planed wells. Total pumpage by pumping wells is maintained constant in calibration period. Table 1 summarized other input parameters that were used for the simulation. The simulated results are shown in the Figure 9. It can be seen the interface would be hardly moved although the cones of depression extend to the position of the planed subsurface dam.

Table 1. Input parameters for subsurface dam simulation

| | |
|---|---|
| Domain | Square elements with spacing of 25 m |
| Permeability | $K$ = 1.2~5.8×$10^{-4}$ m/s |
| Porosity | $n_e$ = 0.21~0.3 |
| Plan pumping well | 4 wells |
| Pumping plan: ($m^3$/d) | $Q_p1$ = 100, $Q_p2$ = 150, $Q_p3$ = 200,$Q_p4$ = 250 |
| The permeability of the subsurface dam | $K_d$ = 1.2×$10^{-7}$ m/s(Figure 5.3) |

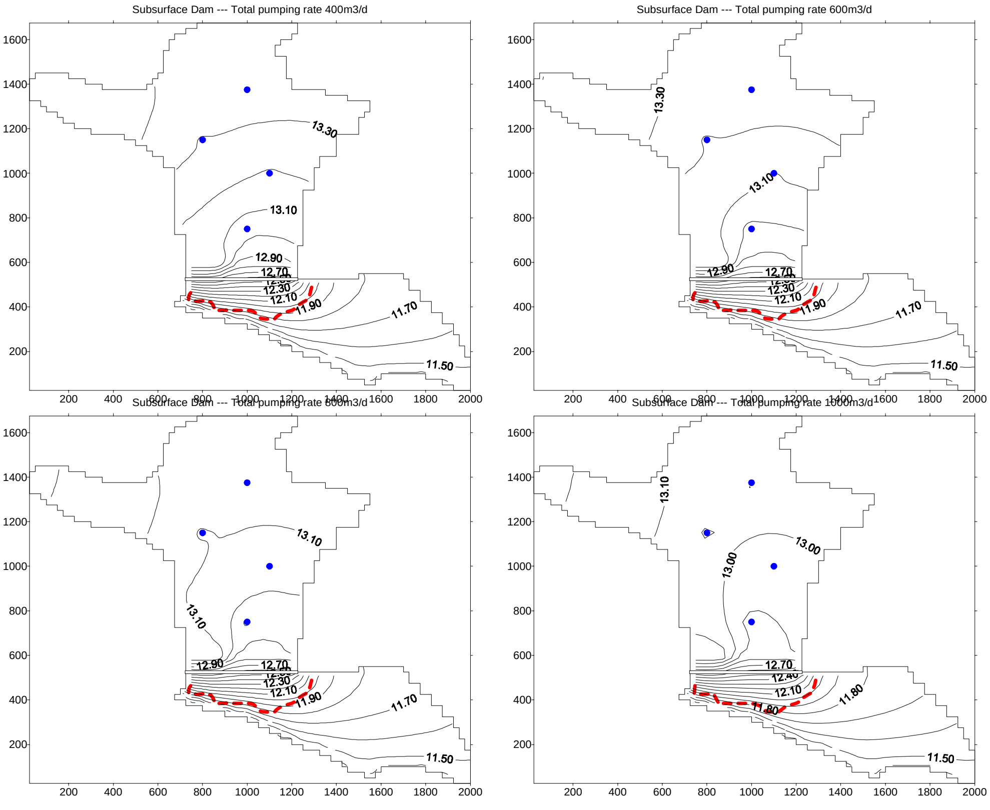


Figure 9 The groundwater tables and position of the interface

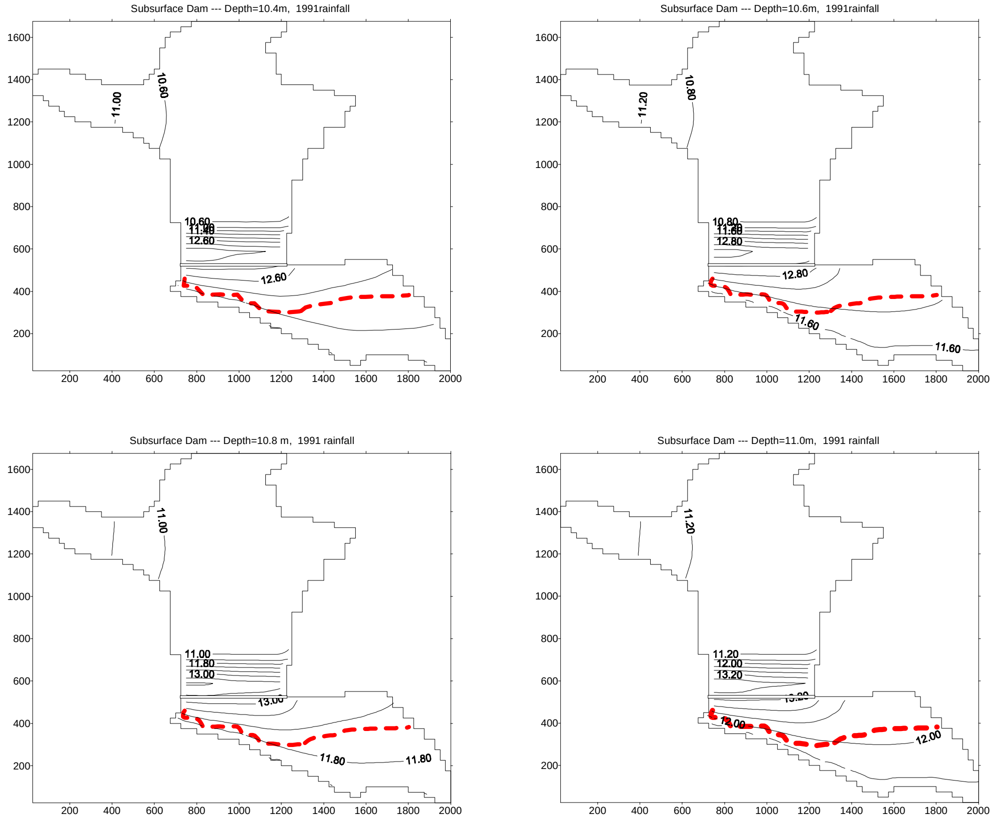
*The collecting water ditch scheme*

Consequently, by the scheme of the collecting water ditch, groundwater levels were changed on five elevations at all of the collecting water ditches. Table 2 summarized input parameters that were used for the simulation.

Table 2. Input parameters for subsurface dam simulation

| For collecting water ditch: | Distribution of the ditches |
|---|---|
| Ditch water level (E.L.m) | Gwl = 10.4, Gw2 =10.6, Gw3 = 10.8, Gw4 = 11.0 m |

The prediction results clearly indicate that even with the different elevation of the groundwater level, the interface would always maintain at the safe position. Figures 10 show the simulation results of the groundwater tables and position of the interface at lateral.


Subsurface Dam --- Depth=10.4m, 1991rainfall

Subsurface Dam --- Depth=10.6m, 1991rainfall

Subsurface Dam --- Depth=10.8 m, 1991 rainfall

Subsurface Dam --- Depth=11.0m, 1991 rainfall

Figure 10 The groundwater tables and position of the interface

Development groundwater resource has led to a lowering of groundwater levels in the coastal phreatic aquifer. Advanced interface indicated the gradual inland movement of seawater along the northern coast. However, by establishing an impervious subsurface dam in the aquifer system, the problem of the seawater intrusion would be solved.

*The Management of the Aquifer*

Because of the overlap and interference among the pumping well, the scheme of collecting water ditch is suggested to adopt in future groundwater development. The typical precipitation likes as drought year (1991); average year (1989) and flood year (1988) were simulated respectively. Figure 11 shows the increase available groundwater in the different annual precipitation on the varied elevation It is worthwhile to note that, under construction subsurface dam, the maximum safe drainage rate is $2.27\times10^5$ $m^3$/y in drought year and $3.73\times10^5$ $m^3$/y in flood year at 10.2m elevation.

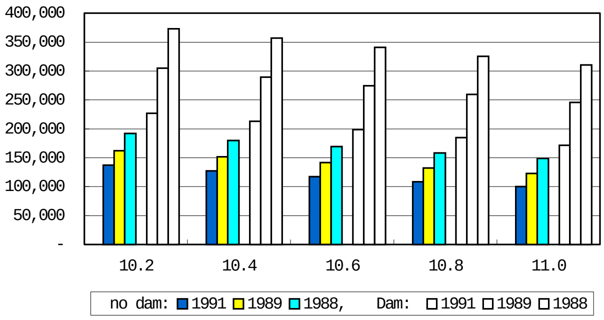


Figure 11 The captured available groundwater within the typical year rainfall

The fundamental issue of groundwater management is its sustainability under development condition, which will affect the long-term viability of the area. As it is defined here, sustainability is the ability of the aquifer to supply water to users without being depleted during the planning period. Sustainability implies the attainment of a new dynamic equilibrium under conditions of widespread development. For equilibrium to occur, withdrawals from the aquifer must induce either additional recharge to the aquifer and reduce discharge from the aquifer, or both. These decreases will continue until changes in recharge and discharge balance withdrawals from the aquifer. The most direct evidence of this new balance is long-term stability of hydraulic heads in the aquifer.

Based on the rainfall trend in recent years, the long-term simulations were made. The simulation result shown that the subsurface dam is an effect method to increase available groundwater resource and prevent seawater intrusion into the aquifer. For 10 years simulation, the accumulation of available fresh groundwater will reach to $3.6\times10^6$ $m^3$ at the 10.2-m elevation in this aquifer system. Figure 12 shows accumulation available groundwater at the ditch's water level of 10.2m, 10.6m, and 11.0-m elevation. The model simulations suggest that groundwater would be available freshwater resource throughout the southern part area of the subsurface dam.

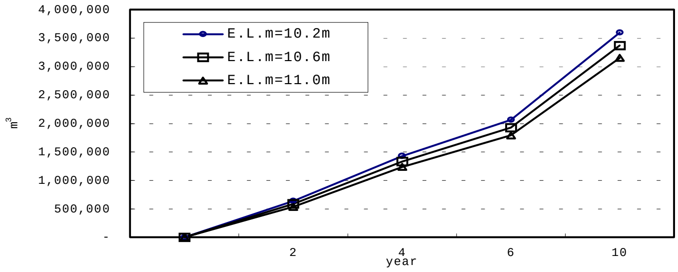


Figure 12 Accumulation available groundwater

Because of the interference among the pumping wells, the scheme of collecting water ditch is suggested to adopt in future groundwater development. In different recharge years, the nearly double amounts of fresh groundwater can be captured as building a subsurface dam. The function of the subsurface dam is obvious effect for capturing the groundwater outflow and protecting the groundwater resource from seawater intrusion in the aquifer system.

The aquifer system management is a multi-disciplinary, multi-faceted mechanism offering an adaptive management strategy, which both addresses the issue of resource-use conflicts and provides the necessary policy orientation to control the impacts of human intervention on the physical environment.

At present, the manager is developing a plan, which include developing adequate present and future water supply in the study area. The regional development and freshwater resources are closely related. Water resource management must therefore seek to rationalize the use of island groundwater resources with the goals of sustainable development.

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